Laminar, intermittent and turbulent fluid mud flow

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Abstract

Fluid mud is a hyper-concentrated mixture of water and cohesive sediments with a density above its gelling point. The flow of fluid mud is of practical importance for gravity currents on the bottom of aquatic environments (hyper-concentrated rivers, storm-induced density currents, earthquake-induced sediment avalanches, dredged material dumping, ...) or on land (mud slides and debris flows), and for the pumping of slurries (dredged materials, drilling muds, mine tailings, ...).

Many studies have been conducted to study the slow, laminar shear flow of fluid mud and its characterization by rheology. The equilibrium rheology is best described by a visco-plastic model, i.e. a shear-thinning fluid with a yield stress, and its transient behaviour by thixotropy (Toorman *et al.*, 2014). Based on such a rheological model, one can compute the theoretical laminar flow velocity profile for open-channel (or pipe flow), i.e. a linear profile at the bottom (or pipe wall) going over in plug flow at the free surface (or in the center of the pipe).

Checking local Reynolds number values, it can be shown that it is expected that with only a little extra energy, the flow should be come turbulent in a shear layer near the wall. Few observations exist that demonstrate this. Probably the most interesting data set is available from the flume experiments by Baas *et al.* (2009), which cover flow ranges from laminar to turbulent.

Because no generally valid modelling framework exists for this type of slurry flow, a new approach is presented based on the low-Reynolds extension of the mixing-length theory. It makes use of an empirical damping function, inspired by the original work of Van Driest (1956) and later followed in most other low-Reynolds turbulence models. However, the chosen damping function is defined in terms of a local Reynolds number, which is independent on the wall distance (unlike Van Driest). Moreover, unlike other damping functions, care is taken that the correct asymptotic behaviour of the solution towards both the turbulent and the laminar regime is fulfilled. This relatively simple model is tested in simple 1DV testcases of steady flow over a flat, sloping bottom for the different flow regimes.

Based on this model, the corresponding friction loss in hydraulic transport can be computed, which enables the calculation of the required pumping capacity. Comparison with measured pressure losses from experiments reported in the literature will be performed.

The same turbulence modelling strategy will be useful for the numerical simulation of water over a fluid mud layer. While the flow in the water layer (usually) is turbulent, the shear with the mud bed may induced some mass transport of the mud, but more likely causes disturbance of its surface, eventually leading to mixing over the interface and entrainment of mud into the water column and dilution of part of the mud layer. Nevertheless, the turbulence model should be able to go from the turbulence in the water down to the laminar non-Newtonian movement of the fluid mud.

Based on the work of Reichardt (1951), an empirical correction for the "wake-effect" at the free surface (or pipe center) can be taken into account. This sheds new light on the discussion on whether the value of the von Karman parameter is constant or not in sediment-laden turbulent flow.

Eventually, this turbulence modelling strategy is combined with a new ("wall-distance free") low-Reynolds version of the *k*-epsilon turbulence model. The algebraic model is applied in the wall layer, while the *k*-epsilon model is solved in the outer layer up to the free surface. Preliminary attempts to test this two-layer strategy to the well-documented case of clear water over a smooth surface has revealed that numerical problems occur when the transient shear layer (between the laminar sublayer and the fully-developed turbulent outer layer) has to be resolved within the numerical domain where the *k*-epsilon equations are solved. A practical solution to overcome this problem is under investigation.

The results of this research provide new tools to better analyse and understand the energy consumption over the vertical of sediment-laden flows, and is applicable to both cohesive and non-cohesive sediments.

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